An Effective Power Control Technique for Deploying Wireless Sensor Networks within Specific Scenarios

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Abstract. A major issue for deploying wireless sensor networks (WSN) in scenario with obstacles is how to determine the transmission power levels (TPLs) for the sensor nodes that support the desired network connectivity while minimizing overall power consumption. In such scenarios, an effective TPL control needs to consider the phenomena of propagation barriers and multipath interference since they significantly increase the power consumption. In this work, we present a novel technique for TPL control that estimates for each sensor node's transmitter used within a given scenario how many other sensor nodes it will reach when applying a selected TPL. To evaluate the effectiveness of our approach, we simulated the radio propagation of a WSN for two different indoor scenarios of multiple rooms. Our results showed that our technique selected TPLs that resulted in considerable time and energy savings for the WSN, while identifying TPLs that could overcome the existing propagation barriers.

1 Introduction

In recent years, the availability of Wireless Sensor Networks (WSN) has promoted new models for collecting and broadcasting information with great potential in new application areas, including environmental monitoring, "intelligent" buildings, to name a few.

However, a major problem facing the deployment of WSNs is the limited battery timelife of their sensor nodes that requires each node to efficiently control its transmission power. On the other hand, the maintenance of a certain connectivity degree [1] among the nodes while minimizing their energy consumption are conflicting goals that influence other aspects of the WSN operation as well [2].

In this work, we devised a novel technique that can determine the effective transmission power levels for deploying WSNs in terrains with obstacles. Specifically, given the configuration of obstacles and the distribution of sensor nodes in a particular scenario, the technique determines the effective TPL that should be used for each sensor node so that it minimizes its power consumption and supports the selected connectivity degree. Our technique is based upon two metrics, the Blockage Rate (BR) and the Useful Area Rate (UR). These two metrics help to assess connectivity gain and energy saving by taking into account the average values of radiation parameters, including the rate of electromagnetic emission blockage, the radiation rate outwards the scenario, the effect of multipath interference, and the percentage of radiation effectively used.

To assess the effectiveness of our approach, we simulated the deployment of a WSN in two different indoor scenarios of multiple offices. The results showed that our technique was able to identify power level thresholds to overcome the obstacle barriers, and also to establish effective transmission power levels to maintain a given degree of connectivity with low power consumption.

The remainder of the paper is organized as follows. Section 2 presents related work. In section 3, we describe our technique for establishing the transmission power levels in WSNs. Section 4 presents our experimental methodology and analyzes simulated results. Finally, we conclude the paper in Section 5.

2 Related Work

Many works on power control management of WSNs [2] adopt one of the following strategies. First, by correlating routing with energy saving. Second, using new feedback mechanisms to adjust the medium access control of the WSN nodes so that they can operate at lower transmission power levels. Lastly, and most related to ours, are the works that attempt to find an optimal power level that takes into account the connectivity properties of the network.

Topology Control (TC) is one of the most important techniques used in WSN to reduce energy consumption and radio interference. [3] states several problems related to topology control in WSN and surveys state-of-art solutions that have been proposed to tackle them. Generally, these solutions use a bottom-up approach, such as the Mobilegrid [4] in which the sensor nodes start either from a lower transmission power level (TPL) up to a higher suitable TPL that often is more economic but takes longer to converge, or vice-versa x they start with a higher TPL (K-Neigh [5]) down to a suitable TPL, spending more power though converging faster. In contrast, our technique determines at once the most suitable power level to start with, thus saving energy and time.

The simplest software approach for modeling of radio-wave propagation at high frequencies (VHF to SHF) is semi-empirical, such as the well-known exponential path-loss model [6]. Those models are simple closed-form equations parameterized by distance, frequency, and one or more parameters from the scenario, with coefficients obtained by field measurements. Propagation in both outdoor and indoor environments may be modeled this way, at a rather low computational cost. Actually, to run those models some complementary information regarding the environment is needed.

Radiowave propagation models applied to detailed terrain databases are commonly referred as Site Specific models (SISP) [6]. SISP modeling may adopt conventional semi-empirical prediction, incorporating more details from the scenario, carrying out additional analysis such as diffraction at elevated obstacles, or at buildings' edges, for instance. Such an approach is usually adopted for large environments, mainly for outdoor prediction. Smaller scenarios (usually indoors) may benefit from more complex and accurate approaches such as ray-tracing modeling. In this technique, the main propagation paths (rays) are deterministically found based on the common electromagnetic phenomena of reflection, refraction, and scattering (includes diffraction). Ray-tracing is usually carried out two-fold, either by force or image theory [7].

With the ever growing available numerical capacity, ray-tracing models have increasingly become more attractive as propagation prediction tools. Some researchers even bet that deterministic modeling may prevail in a near future, as the preferred approach for propagation prediction, even outdoors [6].

The most used network simulators in Computer Science [8] are Network Simulator (NS-2) and GlomoSim. Both do not allow obstacles insertions [9]. Only recently more realistic scenarios were incorporated to NS-2 [10], [11]. WSN multipath fading aspects have also been recently discussed in the literature [12].

Regarding simulation aspects, those are the works more closely related to ours. However, unlike those, we propose and evaluate new TPC metrics in scenarios with obstacles and simulate multipath interference effects. Our technique is able to determine the initial TPL and thus saving energy and time.

3 Transmission Power Control Technique

Our technique is based upon two metrics: Blockage Rate (BR) and Useful Area Rate (UR) [13]. In overall, those metrics help to assess connectivity gain and energy savings by taking into account the average values of parameters, including the rate of electromagnetic emission blockage, the radiation rate outwards the scenario, the effect of multipath interference, and the percentage of radiation effectively used.

3.1 Scenario Occupation Profile

In order to calculate BR and UR for a given scenario it should be known in advance. In particular, we can use a Geographic Information System (GIS) to build a Probabilistic Spatial Distribution Map (PSDM). The idea behind PSDM is that distributed devices within a WSN scenario tend to form a specific probabilistic occupation profiles. For example, pedestrians usually walk along sidewalks, gardens and parks. Cars are driven on roads, avenues and so on. Therefore, it is always possible to derive the PSDM using the location of the sensor nodes distributed in a specific scenario, mobility models [14], or calculated by means of a localization system [15] that indicates the probable region where each sensor is located.

Figure 1 shows an example of a receive device's PSDM based on the relative weights of the distributed occupation across the terrain by the transceivers. These weights are obtained from a given probability density. The distribution can be function of time and number of transceivers. It can also be conditional

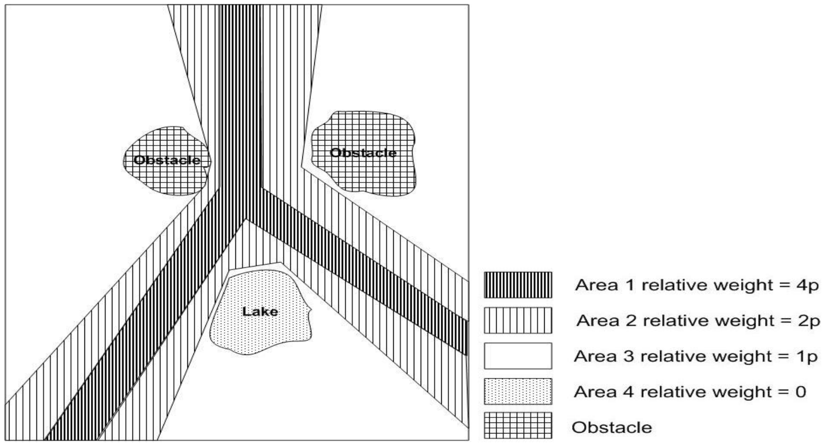

Fig. 1. Probabilistic Spatial Distribution Map (PSDM)

$(P(A \mid B))$. As an example, Figure 1 represents a scenario where the area with $p = 4$ corresponds to streets, $p = 2$ represents sidewalks, $p = 1$ corresponds to gardens, and $p = 0$ represents a lake. PSDM is also a time function[1].

3.2 Blockage Rate (BR)

Figure 2 shows a typical situation where a certain obstacle blocks the electromagnetic signal of transmitter t, establishing four distinct areas regarding the quality of signal reception. The receivers area (RA), the theoretical coverage area not contained in RA, the coverage area contained in RA blocked by the obstacles (E_B) and the area unblocked (E_{NB}). Conceptually, BR expresses the ratio between (E_B) and the sum $(E_B) + (E_{NB})$.

Formally, consider a specific transmitter class located at s position, and assume a specific transmission power level pw, then $BR(t(s, pw))$ is defined by:

$$BR(t(s,pw)) = \frac{\sum_{x \in RA} P(r_j(x) \mid t(s)) B_{CF}(t(s,pw), r_j(x)))}{\sum_{x \in RA} P(r_j(x) \mid t(s)) B_{NF}(t(s,pw), r_j(x)))} \quad (1)$$

In equation (1), $P(r_j(x) \mid t(s))$ represents the probability that the j^{th} receiver, r_j, is found at x position, subjected to a t-type transmitter being located at s position. Note that the expression accommodates clustering (when devices tend to join) and repelling (when there is a minimum distance between devices). The antenna gains of transmitters and receivers are considered in the calculation of the probabilities, as well as the receivers' sensitivities. The function B accounts for the interaction between transmitters - $t(s, pw)$ (transmitter t at

[1] For example, when the battery of a sensor node becomes flat

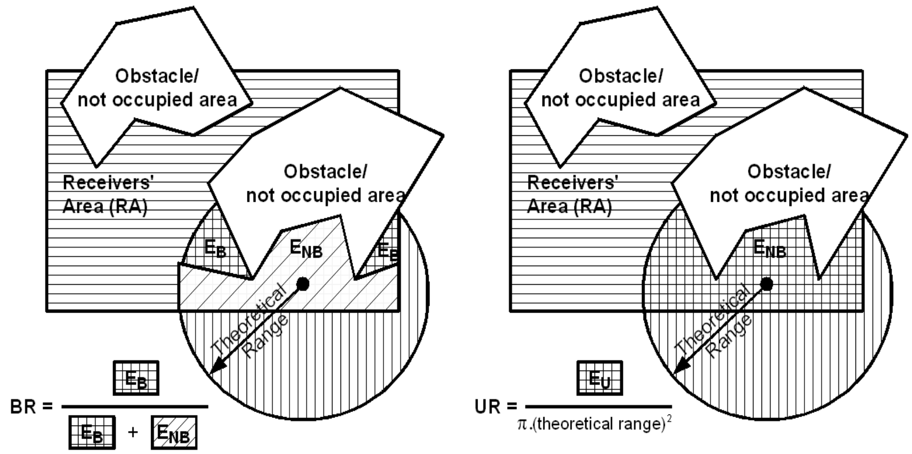

Fig. 2. Blockage Rate and Useful Area Rate

s, emitting a pw power level) - and receivers - (receiver r_j) - within RA. The subscripts $_{CF}$ and $_{NF}$ mean Considering Fading and Not considering Fading.

$B_{CF} \in \{-1, 0, 1\}$. B_{CF} returns 0 when the receiver $r_j(x)$ is in the theoretical coverage area of a transmitter t at a pw power level, the received signal is above the sensitivity and the multipath interference is so weak that it is unable to degrade the data link (a power level threshold must be established to assist this process). Otherwise B_{CF} returns 1, either when the degradation due to multipath is observed or the received signal is below the sensitivity. B_{CF} will return -1 when the receiver is outside the theoretical coverage area, since multipath interference may also cause a constructive effect (at aisles, for example), though the obstacle configuration is such that the transmitted signal is still able to reach the receiver r_j.

$B_{NF} \in \{0, 1\}$. B_{NF} simply considers free-space propagation and the presence of obstacles against direct rays. It returns 1 for all receivers $r_j(x)$ within the theoretical coverage area of the transmitter t at position s - $t(s, pw)$. Otherwise B_{NF} equals zero,i.e, when the receiver r_j is at a position x such that it is either outside (beyond) the theoretical coverage area of t, or behind any obstacle (no direct ray reaches the receiver).

We calculate BR for a specific Transmitter Area (TA), computing the weighted average of all $BR(t(s, pw))$ according to equation (2). Other statistical parameters such as standard deviation, median, maximum, minimum, etc., are also calculated in order to provide the best possible description of the chosen scenario. We may also compute the first and the second derivatives with respect to TPL (pw) to help with the analysis on overcoming propagation barriers.

$$BR(TA, t, pw) = \frac{\sum_{s \in TA} P(t(s)) BR(t(s, pw))}{\sum_{s \in TA} P(t(s))} \tag{2}$$

3.3 Useful Area Rate (UR)

Figure 2 illustrates the notion of Useful Area Rate (UR) that expresses the ratio between the useful and the theoretical coverage area of a transmitter node. The definition of useful coverage area comprises the theoretical coverage area of a transmitter that lies within the receiver area ignoring the obstacles. Therefore, this metric is most concerned with free-space coverage and aspects of signal range in the WSN, thus ignoring multipath effects and scattering. Formally, given a certain transmitter class t, located at s, operating at a power level pw, $UR(t(s, pw))$ is defined by (3):

$$UR(t(s, pw)) = \frac{\sum_{x \in RA} U_{CO}(t(s, pw), r_j(x))}{\sum_{x} U_{NO}(t(s, pw), r_j(x))} \tag{3}$$

Function U verifies the interaction between the theoretical coverage area and the scenario's obstacles. The subscripts $_{CO}$ and $_{NO}$ mean that Considering Obstacles and Not Considering Obstacles, respectively.

$U_{CO} \in \{0, 1\}$. Function U_{CO} returns 1 when the receiver r_j is in the theoretical coverage area, or in RA, or in a position where $P(r_j(x) \mid t(s))$ is not equal to 0. Otherwise, it returns 0.

$U_{NO} \in \{0, 1\}$. U_{NO} quantifies the coverage area, considering r_j's sensitivity. UR mainly aims at the loss effects of propagation paths, neglecting probabilistic distribution of receiver's position that has already been considered in BR.

3.4 Determining the connectivity through BR and UR

Consider $CA(t(s, pw), r_j)$ as the theoretical coverage area of a transmitter t operating at a power level pw for a specific receiver r_j. Yet, consider D as the sensor node density and $t(s, pw) = z$. When we carry out the product:

$$(1 - BR(z)).UR(z).CA(z, r_j)D = C(z) \tag{4}$$

we will get a specific connectivity for that position. We can expand equation (4) to a region, as we made to $BR(TA, t(pw))$, and calculate various statistical moments. The mean, for example, is given by equation (5).

$$C(TA, t(pw), D) = \frac{\sum_{s \in TA} P(t(s)) C(t(s, pw), D)}{\sum_{s \in TA} P(t(s))} \tag{5}$$

3.5 Choosing a suitable transmission power level (TPL)

When we select the TPL of a sensor node to support a given connectivity degree, we have to take into account the fact that its transmitter is unable to know where it is exactly located in the transmitter area. For instance, our transmitter could be located in a place with high UR such as the corner of the area and/or small BR as in an empty space, favoring connectivity. If we assume this situation, we can adopt an optimistic approach. On the other hand, if we assume that our transmitter is in a place with small UR and/or high BR, we can adopt a pessimistic approach. In between them, we will have the average value or the median value.

The values of pw for those approaches can be parameterized by any statistical moments available. It may be the standard deviation, median, maximum, minimum, and quartile values. We could use the standard deviation, specially for a high TPL, because we can compute a large number of points so that we can consider a *gaussian* distribution based on the central limit theorem. In this work, however, our main reference is the median.

It is worth mentioning that the node density may also incorporate the WSN duty cycle. Specifically, suppose that the duty cycle is 10% and the WSN has no synchronizing mechanism, then the actual node density should be divided by 10 to to have it incorporated.

3.6 Using the Technique

The computation of the metrics should be previously performed before starting the WSN operation. Next, the table of values can be stored in each sensor node either manually or broadcasting it to them. In the latter, broadcasting can be performed either by peers that share the WSN or devices with location capabilities. Usually, BR and UR can be computed using either desktop computers or other high-performance computers depending on the WSN size. The sensor nodes store tables with BR and connectivity data in order to choose suitable TPLs. The complexity of choice is $O(n)$, where n is the number of discrete TPLs available.

These metrics should be used in a planned way. Indiscriminate use of BR and UR in a heterogeneous environment would hardly bring energy savings benefits. Ideally, the metrics should be used in small clusters of sensor nodes that can be automatically detected during the data processing by data mining techniques (clustering). In special, a recommended choice is the *k-Medoid Method*, in which the points with the smallest BR values would be considered as cluster centers [16].

4 Simulation

In this section, we evaluate the benefits that BR and UR metrics can offer to establish the TPL scheme for a WSN. Specifically, we simulated the deployment of a WSN in two different indoor scenarios, for which we computed BR, UR, and C, and then used these results to determine the most efficient transmission power levels for the sensor nodes of the WSN for each of the scenarios.

4.1 The Zerkalo Simulator

We developed a simple SISP tool called *Zerkalo* (*mirror* in Russian) based on ray-tracing (images method) that simulates the electromagnetic propagation in a given scenario. Besides free-space propagation, *Zerkalo* also simulates the electromagnetic phenomena of reflection and refraction by computing the multipath interference due to reflections up to a desired order. *Zerkalo*'s algorithm complexity is of $O(n^r)$, where r is the reflection order and n is the number of obstacles.

Zerkalo computes the free-space path loss and both the attenuations and phase changes due to reflection and refraction (based on Fresnel coefficient), as the radiowave propagates within the scenario. In the design of *Zerkalo*, we assumed the so-called *narrowband* hypothesis that considers that the transmitted signal's spectral content is narrow enough around the carrier (dozens or hundreds of kHz depending on the conditions) so that the technique fading can be considered flat [6]. The points most affected by this kind of fading are those close to walls, specially the ones near the corners [12]. *Zerkalo* uses the CGAL [17] as its basic computational library.

4.2 Scenario Test One

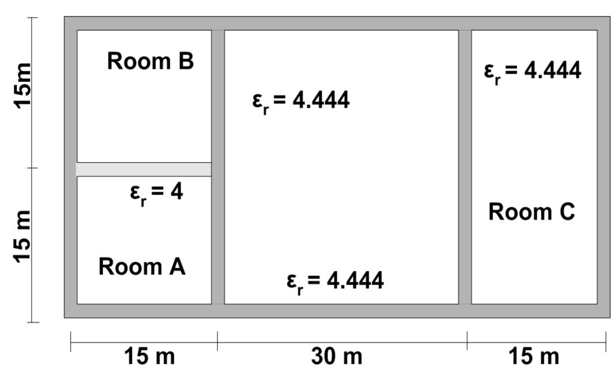

Fig. 3. Scenario Test

To assess the potential benefits of the proposed technique, we considered an office with three standard rooms, one large room, and obstacles as shown in Figure 3. There is a 2 cm wide glass wall between rooms A and B, with relative permittivity equal to 4. The remaining walls are 15 cm wide brick walls with relative permittivity equal to 4.444. In this scenario, the density of occupation of the large room is 0 whereas the other standard rooms have the same homogeneous occupation of 0.1 sensor by square meter. Rooms A, B, and C share a WSN.

We computed the metrics defined at section 3 for transmitters at room A and receivers at rooms A, B and C, considering up to second order reflections[2]. We have also assumed the following test parameters: 0.122 m wavelength, receiver sensitivity for bearing detection about -70 dBm[3], and half wave dipole antennas (1.64 dB gain) for transmission and reception [6]. In the present scenario test, the antennas' heights were half way between floor and roof, such that the major propagation effects were concentrated on the horizontal plane comprising all antennas, simplifying the propagation problem to a 2D analysis.

Regarding to the influence of technique interference, the BR metric uses a threshold value that defines whether or not to consider a resulting fading. For the analysis presented below, we assumed a threshold value of half the power received in the main propagation path that is usually the direct path. Specifically, if the (complex) sum of all the multipath phasors is below half of the main component power, then $B_{CF} = 0$. Otherwise, B_{CF} returns 1 or -1, for destructive or constructive interference, respectively. Figure 4 illustrates how *Zerkalo* computes path loss, with or without multipath interference. The darkest points in Figure 4 represent those most affected by the multipath interference. Observing any propagation radial departing from the illustrated transmitter node (Tx), the expected interference pattern is quite clear in Figure 4, with alternate decaying maximum and minimum, as the observed point moves away from the source.

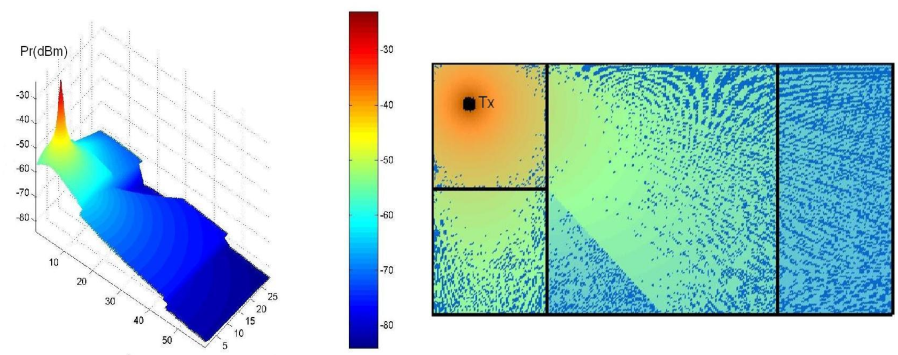

Fig. 4. Radiation without multipath

[2] Research results have shown that only the first reflection has significant power under most situation [18]

[3] This is the specification of Bluetooth standard 1.1. We take this value (-70 dBm) just as a simulation parameter

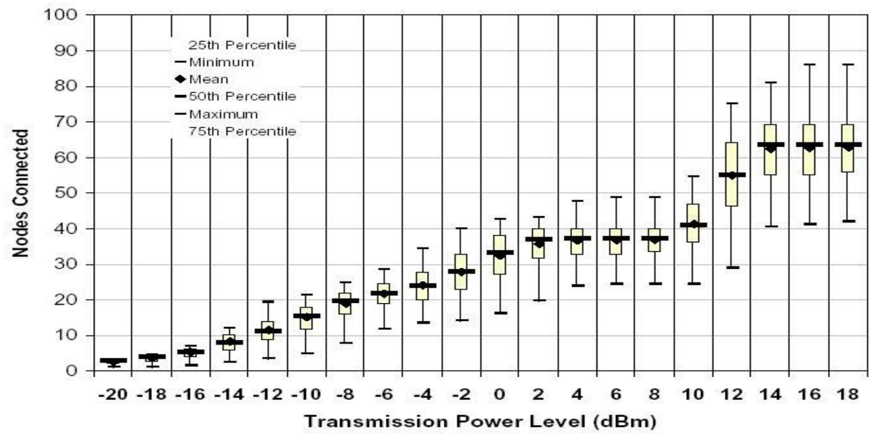

Fig. 5. Connectivity x TPL

Connectivity Aspects We used the equation 4 with the criteria above described for assessing the WSN connectivity. As a result, a table was built and stored in the sensor node with the following statistical parameters: minimum, first quartile, mean, median, third quartile, and maximum. The table had twenty rows (TPL) and six columns (statistics) and is shown in Figure 5.

Let us assume that a given sensor node should be interconnected to other 40 sensor nodes. According to our technique, the sensor node will look up its table checking on possible values that allow it to achieve that connectivity degree. As can be seen in the table, only TPLs set at least to 0 dBm will attend the required connectivity with probability greater than zero. If 0 dBm is chosen, there is a probability of less than 25% of reaching 40 nodes. For TPL between 2 and 8 dBm, the chance is exactly 25% no matter the TPL chosen. In this case, the best TPL choice is 2 dBm, since the energy consumption will be the lowest. Next TPL levels of 10 and 12 dBm indicate that the probability will rise to 50% and 75% in this order. Finally, from 14 dBm upwards, the desired connectivity will always be reached. Similarly, if we want 10 sensor nodes to be reached, the table indicates that the required connectivity will always be reached for TPLs set at least to -6 dBm.

Overall, this example demonstrates the two main properties of our technique: 1) it allows to infer the TPL above which a sensor node would waste power consumption without increasing its connectivity, and 2) it allows the direct use of the energy saving as the main parameter when choosing the connectivity for a WSN.

It is worth mentioning that the present technique selects TPLs considering no feedback from the other WSN nodes, thus gaining more time and energy savings. Thus, an alternative technique is to make use of such feedback data to update information such as changes in the density of sensor nodes. The disadvantage is that it will increase both the energy consumption and processing time.

Our technique has been derived for the collisionless transmission case. However, it can be modified to be applied even when collisions are considered. As an example, we assume that we have a sensor node A transmitting at -12 dBm, and this TPL information is broadcasted with the main data. Also, suppose that another sensor node (B) has an emergency in the same TA while sharing the same connectivity table. Since the channel is occupied by A, the sensor node B has to choose a TPL such that it can overcome the influence of A's transmission and thus it chooses 6 dBm for TPL. According to our technique, the highest number of nodes reached by A will be 20 while the lowest number of nodes reached by B will be 28. Note that sensor node B will reach 8 other nodes in the worst-case scenario, despite of sensor node A being in operation. Furthermore, B will reach 44 sensor nodes in the best-case scenario, which can be calculated by the difference between the highest number of sensor nodes reached by B and the lowest number of sensor nodes reached by A, considering that no other sensor node transmits in the same channel.

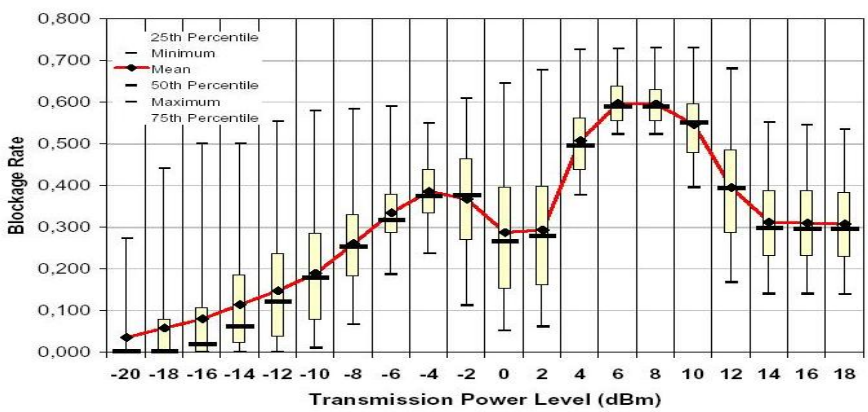

Fig. 6. Scenario Blockage Rate

Blockage Aspects Besides establishing an effective power-aware connectivity, our technique allows to make inference about contention and thresholds to overcome propagation barriers, simply by interpreting BR data. In this scenario test, there are four important barriers splitting room A from rooms B and C: the glass wall, the walls of the empty space, and the empty space itself.

According to the calculated BR values for room A shown at figure 6 and its derivatives (figure 7), we notice that due to the glass wall between rooms A and B, BR grows continuously up to the TPL of -6 dBm ($BR'' = 0$), when this barrier is slightly overcome. The first derivative of BR at -2 dBM ($BR' < 0$) shows the inversion of BR, which means that at a TPL of this magnitude, the glass wall is effectively overcome.

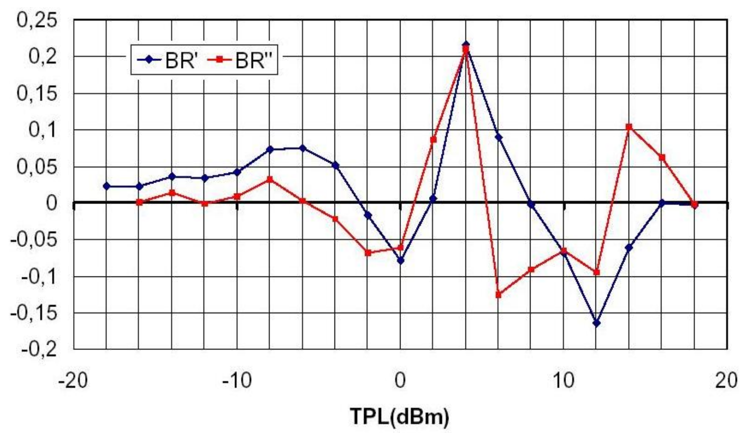

Fig. 7. BR's first and second derivatives

In the previous subsection, we noticed that the connectivity degrees between 2 dBm and 8 dBm are very similar. This was due to the walls of the empty space, as well as the empty space itself. On analyzing BR' at 8 dBm, we verify another inflexion point, at which the electromagnetic radiation starts to overcome those barriers. From 10 dBm upward, the signal also reaches room C, thus decreasing BR and increasing the connectivity. On the other hand, the barriers also help avoiding collisions, since they help to confine the signal transmitted by the sensor node within those barriers.

4.3 Scenario Test Two

The scenario test two is composed of 9 rooms (15x15 m^2), similarly disposed as in the tic-tac-toe game. The rooms are apart by a 15 cm wide brick walls with relative permittivity equal to 4.444. We assume a relatively homogeneous scenario with density occupation of all rooms as being 0.1 sensor by square meter. Figure 8 shows the radiation in the three rooms located at the corner, the lateral, and the center, respectively.

On observing that the connectivity analysis is similar to that of scenario one (and very dependent on BR), we will analyze only the blockage aspects in this section. The BR results (either considering or not the multipath aspects) are shown in Figure 9.

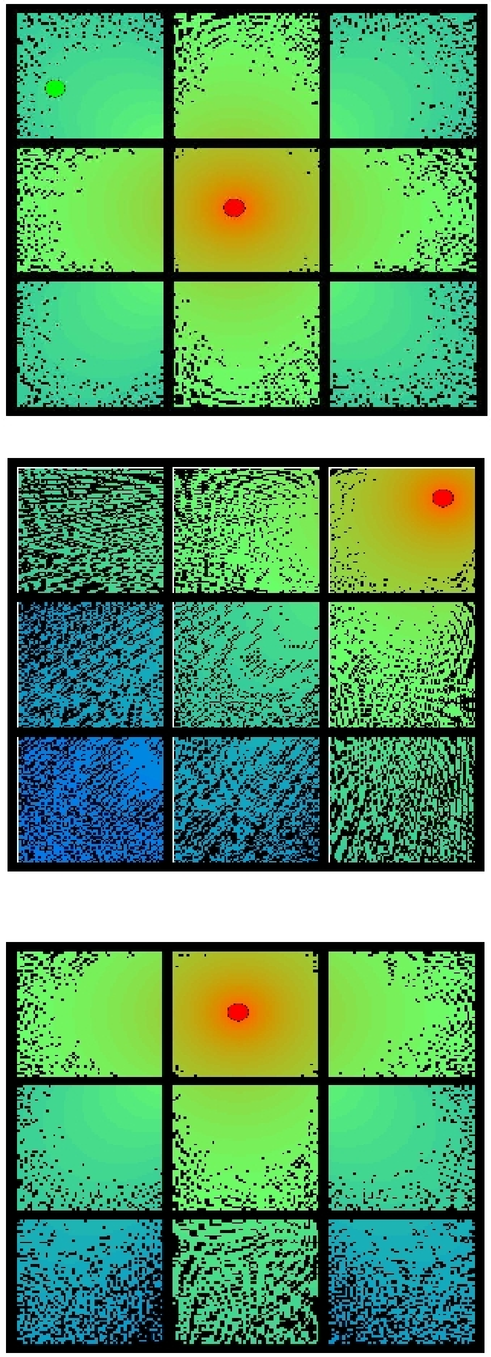

Fig. 8. Radiation of scenario 2

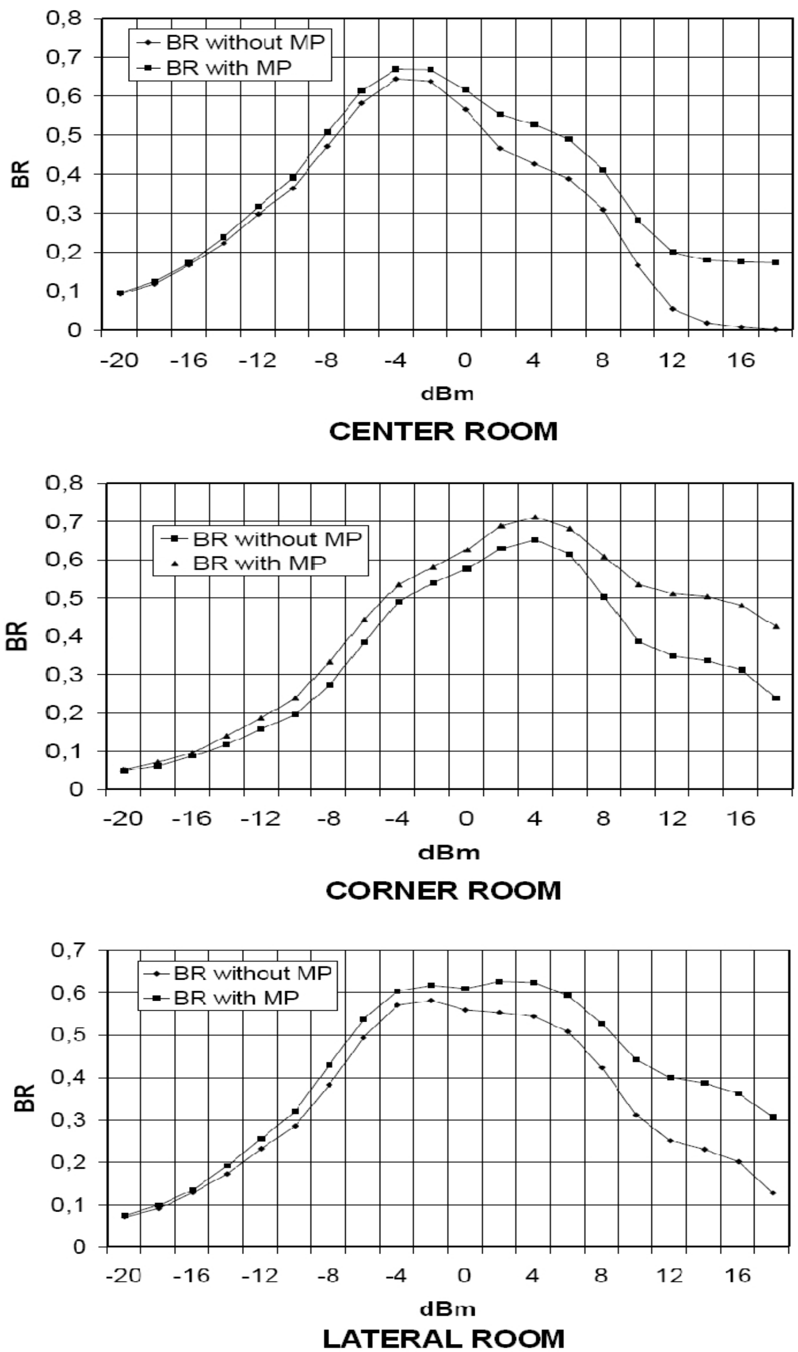

Fig. 9. *BR*s of scenario 2

In contrast with the previous scenario, the present scenario does not have a specific barrier that we can directly identify. However, we have distinct thresholds for each room, specifically 4 dBm for the corner room, a flat summit between -4 dBm and 6 dBm for the lateral room, and a narrow peak between -4 dBm and -2 dBm for the center room. The case of the center room is similar to the case of scenario one, where the peak represents the room's walls. For the lateral and corner rooms, the arrangement of the obstacles forms intrinsic barriers that could be identified by the BRs. Further inferences could be done through the analysis of the first and the second derivate of BRs. For example, in Figure 9 (corner room), the second derivate of BR of corner room would invert the signal at -4 dBm, representing the room's walls. Note that by knowing these information in advance, we can use the techniques described in subsection 4.2.

An important remark is that the multipath interference actually increased BR when compared to the equivalent rates calculated without considering this feature. The ratio between both BRs, i.e. BR calculated with and without interference, was always greater than 1 at all the TPLs (-20 to 18 dBm) as shown in Figure 9. In other words, our technique provides an efficient and simple way to account for the technique effects on the network connectivity, correcting optimistic predictions that would otherwise arise from a simple free-space path loss analysis.

5 Conclusion

This work has proposed a novel technique for deploying wireless sensor networks (WSN) in scenarios with obstacles. The technique is able to support the desired connectivity of WSN under the effects of propagation barriers and multipath fading by determining suitable transmission power levels (TPLs) for sensor nodes that minimize power consumption. The technique made use of two new metrics, the Blockage rate (BR) and the Useful Transmission rate UR that allow the connectivity (C) of sensor nodes to be easily estimated for any chosen TPL.

To evaluate the potential of our technique, we simulated the electromagnetic propagation of two WSN scenario tests of multiple rooms with obstacles in detail. The simulated results showed that the technique could determine the most suitable TPL depending on the required degree of connectivity. Also, it identified TPL thresholds to overcome the existing propagation barriers in the two scenario tests and thus provided means to avoiding contention. Overall, the two main properties of the technique were demonstrated: 1) it allows to infer the TPL above which a sensor node would waste power consumption without increasing its connectivity, and 2) it allows the direct use of the energy saving as the main parameter when choosing the connectivity for a WSN.

We intend to investigate how to take advantage of feedback data to improve our technique, especially by analyzing collision hazards and the hidden terminal problem. We plan to extend our technique to work in 3D scenarios, with different antenna heights, and to aggregate other radio irregularities besides multipath interference.

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